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Computational Models of X-Ray Burst Quenching Times and ^{12}C Nucleosynthesis Following a Superburst

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ABSTRACT

Superbursts are energetic events on neutron stars that are a thousand times more powerful than ordinary type I X-ray bursts. They are believed to be powered by a thermonuclear explosion of accumulated ^{12}C . However, the source of this ^{12}C remains elusive to theoretical calculations and its concentration and ignition depth are both unknown. Here we present the first computational simulations of the nucleosynthesis during the thermal decay of a superburst, where X-ray bursts are quenched. Our calculations of the quenching time verify previous analytical calculations and shed new light on the physics of stable burning at low accretion rates. We show that concentrated ($X_{^{12}\text{C}} \gtrsim 0.40$), although insufficient, amounts of ^{12}C are generated during the several weeks following the superburst where the decaying thermal flux of the superburst stabilizes the burning of the accreted material.

Subject headings: X-rays: bursts — stars: neutron

1. Introduction

Superbursts are believed to be massive thermonuclear explosions of accumulated ^{12}C in the ocean of neutron stars that also exhibit type I X-ray bursts (XRBs) (for a review, see Strohmayer & Bildsten 2006) (Cumming & Bildsten 2001). Following a superburst, normal X-ray burst activity is quenched for several days or weeks (Cornelisse et al. 2002; Kuulkers 2002, 2003) suggesting that the thermal flux of the cooling superburst layer stabilizes the burning of the accretion H and He (Cumming & Macbeth 2004). Superbursts are therefore intimately linked with XRBs.

In this paper, I am not going to attempt self-consistent superburst simulations to supply the thermal flux into the accreting layer of H/He. Instead I will treat the flux of the superburst as a boundary condition and simulate the behavior of the atmosphere in which XRBs eventually take place in the newly accreted H/He matter to calculate the duration between the superburst and the first subsequent XRB (the quenching time) as

well as the nucleosynthesis of ^{12}C in the accreted matter.

After reviewing the computational model in §2, I consider the resulting XRB quenching times in §3, the production of ^{12}C during the post-superburst XRB quenching in §4, and I end in §5 with a conclusion.

2. Computational model

To investigate the production and accumulation of ^{12}C , I use a version of the **AGILE** hydro-code (Liebendörfer et al. 2002) that has been modified for self-consistent time-dependent state-of-the-art XRB simulations. To wit, the code uses an explicit Henyey (Henyey et al. 1959) coupling of an implicit fully general relativistic spherically symmetric conservative hydrodynamics (Liebendörfer et al. 2002), an implicit reaction network solver (Hix & Thielemann 1999), and implicit convective relativistically corrected mixing based on mixing length theory (Thorne 1977). The constituent relations are based on radiative opacities due

to Thompson scattering and free-free absorption (Schatz et al. 1999); conductivities for electron scattering on electrons, ions, phonons, and impurities (Brown 2000); the same 304 isotope network as Fisker et al. (2008) but using ReaclibV0 available from the JINA website¹; an arbitrarily relativistic and arbitrarily degenerate equation of state describing the electron gas; an ideal gas describing the nucleons; a photon gas; a core boundary interface defined by $0.15 \text{ MeV nuc}^{-1}$ (Woosley et al. 2004); and a numerically integrated relativistically corrected static grey atmosphere (Thorne 1977; Weiss et al. 2004).

Our standard model (see Fisker et al. 2008) has a radius of $R = 11.06 \text{ km}$ and a mass of $M = 1.4 M_{\odot}$ leading to a redshift $1 + z = 1.27$ and a surface acceleration of $g = (1 + z)GM/Rc^2 = 1.75 \times 10^{14} \text{ cm s}^{-2}$. The dynamic computational domain is discretized into 129 log-ratioed zones with a column density ranging from from $y = 1.2 \times 10^6 \text{ g cm}^{-2}$ ($P = 5 \times 10^{20} \text{ ergs cm}^{-3}$) to $y = 3.9 \times 10^9 \text{ g cm}^{-2}$ ($P = 7.5 \times 10^{23} \text{ ergs cm}^{-3}$). This is sufficient for the burst solutions to be numerically converged (Fisker et al. 2006). It is the same code and model used and described more detail in Fisker et al. (2006, 2008) except for the inner boundary modification described below.

2.1. Inner boundary luminosity

The computational demands required to follow the burning numerically for weeks of simulation time are extensive, the results in this paper describe the weakest superbursts in the parameter space explored by Cumming & Macbeth (2004), since weak superbursts are expected to have shorter quenching times and thus require less CPU-time. The effect of the superburst on the surface layer in which the XRB take place is described by the thermal superburst cooling flux solution of Cumming & Macbeth (2004), where the cooling time is given by

$$t_{cool} = 3.8 \text{ hrs } y_{12}^{3/4} \left(\frac{Y_e < Z^2/A > \Lambda_{ei}}{6} \right) \left(\frac{g_{14}}{2.45} \right)^{-5/4}. \quad (1)$$

Here $Y_e = \sum XZ/A$ with $X_{56\text{Fe}} = 1$ so $Y_e(^{56}\text{Fe}) = Z/A = 28/56 = 0.5$, and $y_{12} \equiv y/(10^{12} \text{ g cm}^{-2})$ is the depth of the superburst. Note that y_{12} is assumed to be an independent parameter whereas

it could be a function of \dot{M} as well as the accretion composition. In this study these parameters are not controlled since a self-consistent ignition model does not yet exist. According to Schatz et al. (1999) $\Lambda_{ei}(\rho = 3 \times 10^8 \text{ g cm}^{-3}, T = 3 \times 10^9 \text{ K}, ^{56}\text{Fe}) = 1.21$ (Schatz et al. 1999). We use $g_{14} = 1.75$ (see §2 above) and $y_{12} = 1$ resulting in

$$t_{cool} = 8.17 \text{ hrs}. \quad (2)$$

For $t < t_{cool}$

$$L_{cool} = 3.1 \times 10^{37} \text{ ergs s}^{-1} t_{hr}^{-1/5} X_{0.1^{12}C}^{7/4} \times [1 - \exp(-0.63 t_{cool}^{4/3} X_{0.1^{12}C}^{-5/4} t_{hr}^{-1.13})]. \quad (3)$$

For $t > t_{cool}$

$$L_{cool} = 2 \times 10^{37} \text{ ergs s}^{-1} (t_{hr}/t_{cool})^{-4/3} X_{0.1^{12}C}^{1/2}. \quad (4)$$

When the luminosity from Eqs. 4–4 drops below the steady state luminosity from nuclear reactions in the ocean and core, the core luminosity is set to $0.15 \text{ MeV nuc}^{-1}$ (Woosley et al. 2004) whence

$$L = \max(L_{cool}, \dot{M} \cdot 0.15 \text{ MeV nuc}^{-1}). \quad (5)$$

3. Quenching times

Figure 1 shows the simulated quenching time until the first burst for the model described in §2. Our calculations show a power-law relationship between the accretion rate and the quenching time for $\dot{M} > 0.12$. For lower accretion rates, there is no accurate relationship as the boundary flux from the cooling superburst cooling and the $0.15 \text{ MeV nuc}^{-1}$ flux becomes comparable to the energy released from the hot CNO-cycle and the rp -process decoupling the quenching time from the accretion rate and the cooling process.

It should be noted that numerical XRB models are not necessarily accurate (although they are consistent and precise indicating that time-dependent one-dimensional models are mature but insufficient to fully describe all aspects of the XRB system). For instance, Fisker et al. (2003); Heger et al. (2007); Fisker et al. (2007) find a critical transition point between stable and unstable burning of $1.4\text{--}1.8 \dot{M}_{Edd}$. No bursts have been observed above $0.3 \dot{M}_{Edd}$, which suggests that the accretion process is concentrated to make the local accretion rate higher (Bildsten 2000). It is possible that the accretion rate in the following conclusions

¹<http://www.nsl.msu.edu/~nero/db/>

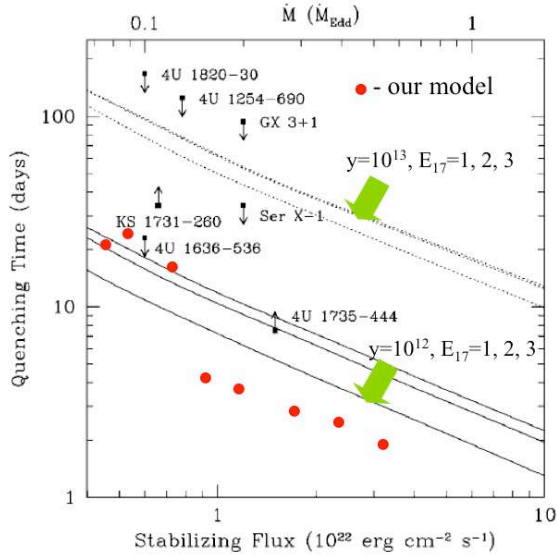


Fig. 1.— The figure shows the quenching time as a function of the accretion rate. Presented are analytical solutions (Cumming & Macbeth 2004) and computational solutions (this paper) for $E_{17} = 0.1$ and $y = 10^{12}$ g/cm².

has to be scaled down to compare to observations. If this is true and the computed critical accretion rate has to be shifted by a factor 5–6. Figure 1 suggests that superbursts are more powerful than the weak burst simulated here. Future calculations of longer tailed superbursts are planned.

3.1. Stabilizing core flux

From Fig 2 we see that the model prediction follows a power law like the analytic prediction for $\dot{M} > 0.12$. For low values of \dot{M} , the model bursts later than the power-law based on the larger accretion rates predicts. Keeping in mind that the accretion rate probably has to be rescaled, the low values of \dot{M} are not useful for deriving any information about the superburst based on the quenching time. For the higher (and likely more realistic) values, our model predicts a stabilizing flux approximately a factor 5 higher than the value derived by Eq. 5 in Cumming & Macbeth (2004).

4. Nucleosynthesis

While matter is burning stably at temperatures above 0.4 GK, ¹²C is made as the He produced in

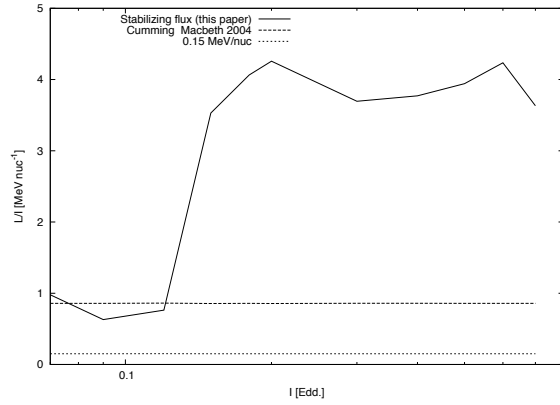


Fig. 2.— The figure shows the stabilizing flux (solid line) as a function of accretion rate along with the analytical prediction (dashed line) from (Cumming & Macbeth 2004). Also shown is the 0.15 MeV/nuc crust flux (dotted line).

the HCNO process burns into ¹²C via the triple-alpha process. Compared to XRB ashes with an average mass > 60 , the dominance of lighter particles lowers the opacity which in turn results in a lower temperature gradient. A lower temperature gradient stabilizes the burning against the explosive runaway as temperatures stay below 0.4 GK until all ⁴He has been converted to a combination of ¹²C and ¹⁶O. This is something that has not been previously explored and will be a subject of a later paper. Figure 3 shows the mass fraction of carbon as a function of relativistic column density for different accretion rates after $y = 8 \times 10^9$ g cm⁻² has been accreted.

While none of the models presented in this study creates enough ¹²C to power a superburst during the quenching time, it supports the idea that the ¹²C that fuels the superburst is generated during periods of low temperature stable burning. If the values in this study are representative, the concentration of ¹²C may be as high as 50% compared to the optimistic 10% that results from studies of stable burning at higher temperatures (Schatz et al. 1999). Since our model shows more ¹²C than previously expected, this would lower the theoretical recurrence time of superbursts by several factors.

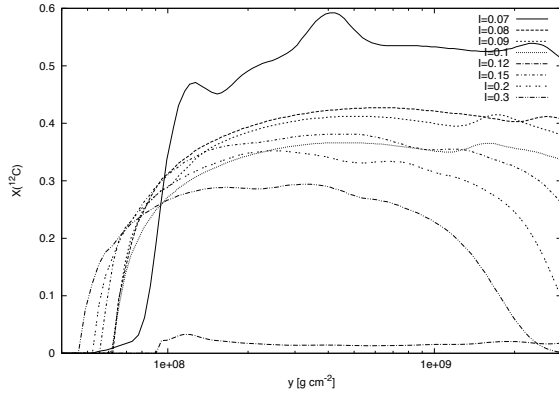


Fig. 3.— The figure shows the distribution of ^{12}C for different accretion rates after $y = 8 \times 10^9 \text{ g/cm}^2$ has been accreted. The amount of surviving ^{12}C depends on the accretion rate.

5. Conclusion

Quenching provides a timed test of stability. Our quenching calculations show that bursts appear sooner than observed. This means that burning is more unstable in one-dimensional computational models, suggesting that additional physics is required in our models. Stable burning during the quenched phase following a superburst shows that the concentration of ^{12}C may be as high as 50%. Since stable burning is needed to generate ^{12}C Schatz et al. (1999), the incompleteness of one-dimensional models might provide a way to generate sufficient carbon at the observed accretion ranges between 0.1 and $0.3M_{\text{Edd}}$ where one-dimensional models otherwise show insufficient amounts of carbon. This will be the topic of a future paper.

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REFERENCES

- Bildsten, L. 2000, in *Cosmic Explosions*, ed. S. S. Holt & W. W. Zhang (AIP), 359
- Brown, E. F. 2000, *Astrophys. J.*, 531, 988
- Cornelisse, R., Kuulkers, E., J. J. M. In't Zand,
- Verbunt, F., & Heise, J. 2002, *Astron. Astrophys.*, 382, 174
- Cumming, A. & Bildsten, L. 2001, *Astrophys. J. Lett.*, 559, L127
- Cumming, A. & Macbeth, J. 2004, *Astrophys. J. Lett.*, 603, L37
- Fisker, J. L., Görres, J., Wiescher, M., & Davids, B. 2006, *Astrophys. J.*, 650, 332
- Fisker, J. L., Hix, W. R., Liebendörfer, M., & Thielemann, F.-K. 2003, *Nucl. Phys.*, A718, 614
- Fisker, J. L., Schatz, H., & Thielemann, F.-K. 2008, *Astrophys. J. Suppl.*, 174, 261
- Fisker, J. L., Tan, W., Görres, J., Wiescher, M., & Cooper, R. L. 2007, *Astrophys. J.*, 665, 637
- Heger, A., Cumming, A., & Woosley, S. E. 2007, accepted for publ. in *Astrophys. J.*, (astro-ph/0511292)
- Heney, L. G., Wilets, L., Böhm, K. H., Lelevier, R., & Levee, R. D. 1959, *Astrophys. J.*, 129, 628
- Hix, W. R. & Thielemann, F.-K. 1999, *J. Comput. Appl. Math.*, 109, 321
- Kuulkers, E. 2002, *Astron. Astrophys.*, 383, L5
- Kuulkers, E. 2003, in *The Restless High-Energy Universe*, ed. E. P. J. van den Heuvel, J. J. M. In't Zand, & R. A. M. J. Wijers (Elsevier)
- Liebendörfer, M., Rosswog, S., & Thielemann, F.-K. 2002, *Astrophys. J. Suppl.*, 141, 229
- Schatz, H., Bildsten, L., Cumming, A., & Wiescher, M. 1999, *Astrophys. J.*, 524, 1014
- Strohmayer, T. E. & Bildsten, L. 2006, in *Compact Stellar X-ray Sources*, ed. W. H. G. Lewin & M. van der Klis (Cambridge University Press)
- Thorne, K. S. 1977, *Astrophys. J.*, 212, 825
- Weiss, A., Hillebrandt, W., Thomas, H.-C., & Ritter, H. 2004, *Cox & Giuli's Principles of Stellar Structure* (Cambridge, UK: Cambridge Scientific Publishers)

Woosley, S. E., Heger, A., Cumming, A., Hoffman,
R. D., Pruet, J., Rauscher, T., Fisker, J. L.,
Schatz, H., Brown, B. A., & Wiescher, M. 2004,
Astrophys. J. Suppl., 151, 75